

ON OBSERVATION OF $e^+e^- \rightarrow b\bar{b}Z^0$ AT LEP II WITH TWO HIGGS DOUBLETS

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Abstract

We study possible observational effects of the two Higgs doublets in the $e^+e^- \rightarrow b\bar{b}Z^0$ at the LEP II energy. We have found that the observational values can be obviously different from that predicted by the minimal Standard Model (MSM), but the results depend on the parameters of the extended model. The possibilities of the observation are discussed in some details.

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I Introduction

The Standard Model (SM) has achieved great successes in almost all fields of phenomenology of high energy physics so far. Especially, the top quark mass has been published as $176 \pm 8(\text{stat.}) \pm 10(\text{sys.})$ GeV [1] and $199^{+19}_{-21}(\text{stat.}) \pm 22(\text{sys.})$ GeV [2], thus the three generation structure of the SM is complete. The only still obscure part in the theory is the Higgs sector, which is crucial to the mechanism of the Spontaneous Symmetry Breaking (SSB) of $SU_L(2) \times U_Y(1)$. Therefore, more attention will be focused on the "Higgs hunting" within a wide energy range [3].

The Higgs hunting includes two-folds. The first is to seek for the existence evidence of Higgs bosons through all available experiments, whereas the other is to test if the Higgs sector is indeed that of the Minimal Standard Model or an alternative, for example, an extension with two or multi Higgs doublets.

There has been much effort to search for the Minimal Standard Model (MSM) Higgs at lower energies of LEP I, but so far no success has ever been reported. With the top-quark being discovered, one cannot elude this acute question now. LEP II will open a new place for Higgs hunting, because clearer signals for heavier Higgs are expected above the relatively low background. Recently Boos and Dubinin estimated the Higgs signal at process $e^+e^- \rightarrow b\bar{b}Z^0$ [4] and they found that the ratio of the Higgs signal versus the background may approach to unity as $\sqrt{s} \sim 200$ GeV provided $m_H \sim 100$ GeV. If the MSM is right, namely only one neutral Higgs exists, the situation for determining the mass of Higgs is optimistic from this estimate on the suggested measurement. Because there is no any free parameter except the Higgs mass at the tree level, a precise data of the cross section and differential cross section of $e^+e^- \rightarrow b\bar{b}Z^0$ would pin down the Higgs mass almost, if $M_H \leq 100\text{GeV}/c^2$. However, if there are more Higgs doublets, it will be another story.

In fact, search for some mechanisms beyond the Minimal Standard Model (MSM) is also interesting for both experimentalists and theoretician of high energy physics

[5]. The "minimal" extended Standard Model(ESM) is the gauge theory $SU_L(2) \times U_Y(1)$ with an extended Higgs sector consisting of two Higgs doublets [6]. If the Higgs sector is indeed more complicated, they may also play roles in the LEP II, such as $e^+e^- \rightarrow b\bar{b}Z^0$, The neutral Higgs being real or virtual, can directly contribute to the process, so it may provide us with the information of Higgs sector.

Recently, a more accurate measurements on $B \rightarrow K^*\gamma$ and $B \rightarrow X_s + \gamma$ set an upper limit to $b \rightarrow s\gamma$ transition and establish more stringent constraints to all the extended Standard Models on the Higgs sector. [7], [8] and [9]. When a special extended Standard Model is applied to the concerned process, the constraint must be taken care of seriously.

For the cross section evaluation of $e^+e^- \rightarrow b\bar{b}Z^0$, we will show below that just because of existence of more neutral Higgs, the situation becomes much more complicated and one cannot be so optimistic about hunting Higgs from the data.

In this work, we analyze the contribution of two Higgs doublet model to $e^+e^- \rightarrow b\bar{b}Z^0$, it is noted that existence of the second neutral Higgs particle h^0 can cause an obvious difference at the differential cross section from that by H^0 only. This result suggests that if only total cross section of $e^+e^- \rightarrow b\bar{b}Z^0$ is measured, the obtained value cannot determine the Higgs mass unless there is only one Higgs doublet, however it indeed can if measuring the differential cross section with respect to $(p_2 + p_3)^2 \equiv s_2$ precisely where p_2 and p_3 are the momenta of b and \bar{b} respectively.

II The extended Standard Model with two Higgs doublets

The general description of the models can be found in ref. [5]. Here we just give some necessary information to make the paper more self-content.

There are two types of the model where the quarks gain masses in different ways and we will denote them as Model I and Model II as in the literature.

The key parameter is β which is defined as

$$\tan\beta = v_2/v_1 \quad (1)$$

where v_1 and v_2 are the vacuum expectation values (VEV) of the two Higgs doublets. In model I, quarks and leptons gain masses only from the second Higgs doublet while the first Higgs doublet decouples. In contrast, in model II, d-type quarks and leptons obtain masses from the first doublet whereas u-type quarks from the second doublet. There are three neutral bosons H^0, h^0 and A^0 remain as real particles after SSB, but since A^0 is a CP-odd boson, in our case (at the tree level) it does not contribute at all.

The Lagrangian for Higgs-fermion coupling can read

$$\begin{aligned} L_{Hf\bar{f}} = & -\frac{g}{2M_W \sin\beta} \bar{D} M_D D (H^0 \sin\alpha + h^0 \cos\alpha) - \frac{ig \cot\beta}{2M_W} \bar{D} M_D \gamma_5 D A^0 \quad (2) \\ & -\frac{g}{2M_W \sin\beta} \bar{U} M_U U (H^0 \sin\alpha + h^0 \cos\alpha) + \frac{ig \cot\beta}{2M_W} \bar{U} M_U \gamma_5 U A^0 \\ & + \frac{g \cos\beta}{2\sqrt{2}M_W} (H^+ \bar{U} [M_U K(1 - \gamma_5) - K M_D(1 + \gamma_5)] D + h.c.) \end{aligned}$$

for Model I. In contrast, the Model II interaction is

$$\begin{aligned} L_{Hf\bar{f}} = & -\frac{g}{2M_W \cos\beta} \bar{D} M_D D (H^0 \cos\alpha - h^0 \sin\alpha) + \frac{ig \tan\beta}{2M_W} \bar{D} M_D \gamma_5 D A^0 \quad (3) \\ & -\frac{g}{2M_W \sin\beta} \bar{U} M_U U (H^0 \sin\alpha + h^0 \cos\alpha) + \frac{ig \cot\beta}{2M_W} \bar{U} M_U \gamma_5 U A^0 \\ & + \frac{g}{2\sqrt{2}M_W} (H^+ \bar{U} \cot\beta [M_U K(1 - \gamma_5) + \tan\beta K M_D(1 + \gamma_5)] D + h.c.), \end{aligned}$$

where K is the Cabibbo-Kabayashi-Maskawa matrix, M_U and M_D are the mass matrices of the u-type and d-type quarks, α denotes a mixing between H^0 and h^0 as

$$H^0 = \sqrt{2}[(\text{Re}\phi_1^0 - v_1) \cos\alpha + (\text{Re}\phi_2^0 - v_2) \sin\alpha] \quad (4)$$

$$h^0 = \sqrt{2}[-(\text{Re}\phi_1^0 - v_1) \sin\alpha + (\text{Re}\phi_2^0 - v_2) \cos\alpha]. \quad (5)$$

Since none of the parameters M_{H^0}, M_{h^0}, β and α is determined experimentally, the extra Higgs doublet increases complexity for identifying Higgs and we will dis-

cuss the measurement problem later.

III The cross section and differential cross section of $e^+e^- \rightarrow b\bar{b}Z^0$

For the MSM, totally there are nine different Feynman diagrams at the tree level, which are given in ref.[4], however, in the ESM, because of existence of h^0 , the diagram (1-3) of ref.[4] should be split into two diagrams corresponding to H^0 and h^0 respectively. Being explicitly, we demonstrate the diagrams in Fig.1 of this paper. The ten diagrams interfere, so the calculation is tedious but straightforward. We first write down the amplitude contributed from the ten Feynman diagrams and then employ a standard program for numerical evaluation of the cross section.

The propagator of H^0 and h^0 is written as

$$\Delta = \frac{i}{p^2 - m_H^2 + i\Gamma_H m_H} \quad (6)$$

where Γ_H and m_H are the mass and width of H^0 or h^0 respectively.

At the tree level, Γ_{H^0} , Γ_{h^0} in model I and model II can be expressed as

$$\Gamma_{H^0(\text{or } h^0)} = \frac{G_F}{4\sqrt{2}\pi} M_{H^0} [3A\beta_c^3 m_c^2 + B(3\beta_b^3 m_b^2 + \beta_\tau^3 m_\tau^2)] \quad (7)$$

where

$$\beta_f^2 = 1 - \frac{4m_f^2}{m_\phi^2} \quad (\phi = H^0 \text{ or } h^0) \quad (8)$$

In model I, $A = (\frac{\sin\alpha}{\sin\beta})^2$, $B = (\frac{\sin\alpha}{\sin\beta})^2$ for H^0 , $A = (\frac{\cos\alpha}{\sin\beta})^2$, $B = (\frac{\cos\alpha}{\sin\beta})^2$ for h^0 , whereas in Model II, $A = (\frac{\sin\alpha}{\sin\beta})^2$, $B = (\frac{\cos\alpha}{\cos\beta})^2$ for H^0 , $A = (\frac{\cos\alpha}{\sin\beta})^2$, $B = (\frac{\sin\alpha}{\cos\beta})^2$ for h^0 .

One alternative way to analyze the data is to measure the differential cross section with respect to the invariant mass of $(p_b + p_{\bar{b}})^2 \equiv s_2$. The interest is obvious: in the three body final state, the whole phase space integration can smear out some information. Explicitly, if the b and \bar{b} come from $b\bar{b}H^0$ and/or $b\bar{b}h^0$ vertices, as $H^0(h^0)$ and the invariant mass of the $b\bar{b}$ pair crosses the pole, the differential cross section can give rise to a peak.

Just as pointed out by ref.[4], an important feature is the large ratio of the Higgs signal to the rest electro-weak background. For the convenience of later discussions, we give the explicit expression of $\frac{d\sigma}{ds_2}$ for which only the Higgs, H^0 and h^0 contributions are taken into account.

$$\begin{aligned} \frac{d\sigma}{ds_2} = & \frac{3}{128\pi^3 s^2} \left(\frac{g^3 m_b}{8C_W^3} \right)^2 (1 + (1 - 4S_W^2)^2) \frac{1}{s_2} \lambda^{1/2}(s_2, m_b^2, m_b^2) \lambda^{1/2}(s, M_Z^2, s_2) \cdot \\ & \left\{ s + \frac{1}{4M_Z^2} [(s + M_Z^2 - s_2)^2 - \frac{1}{3} \lambda(s, M_Z^2, s_2)] \right\} \cdot \left(\frac{s_2}{2} - 2m_b^2 \right) \cdot \frac{1}{(s - M_Z^2)^2 + \Gamma_Z^2 M_Z^2} \\ & \times \left| \frac{1}{(s_2 - M_{H^0}^2) + i\Gamma_{H^0} M_{H^0}} \cos(\beta - \alpha) c_1 \right. \\ & \left. + \frac{1}{(s_2 - M_{h^0}^2) + i\Gamma_{h^0} M_{h^0}} \sin(\beta - \alpha) c_2 \right|^2 \end{aligned} \quad (9)$$

where

$$\lambda(a, b, c) \equiv a^2 + b^2 + c^2 - 2ab - 2bc - 2ca$$

$S_W \equiv \sin\theta_W$, $C_W \equiv \cos\theta_W$, θ_W is the Weinberg angle, $c_1 = \sin\alpha/\sin\beta$, $c_2 = \cos\alpha/\sin\beta$ for model I, $c_1 = -\cos\alpha/\cos\beta$, $c_2 = \sin\alpha/\cos\beta$ for Model II, and $s = (p + p')^2$ with p and p' being the momenta of electron and positron.

Boos and Dubinin [4] showed that the interference between the "signal" diagram from Higgs and the other eight background diagrams is small compared to itself of the signal and background at the peak of the Higgs resonance and the places far away from the peak respectively, so one can investigate the signal of Higgs by directly observing the difference of the differential cross section from that predicted by the well-understood background. The situation for the extended Standard Model with two Higgs doublets is similar: the interference of the signal caused by H^0 and h^0 with the eight background diagrams being small. Therefore we can also study the change of the cross section induced by the two Higgs bosons in comparison with the background. Therefore it makes sense that in the figures for differential cross sections, we plot the total contributions and the part from only the Higgs bosons separately.

Now, let us turn to the numerical analysis.

IV The signal about Higgs and the background

As aforementioned, if the MSM is valid, a precise measurement on the cross section of $e^+e^- \rightarrow b\bar{b}Z^0$ would determine the Higgs mass, but if the second Higgs doublet exists, it is more complicated and uncertain.

The Feynman diagrams which concern H^0 and h^0 are only (3) and (4) of Fig.1. Since all the four parameters M_{H^0} , M_{h^0} , α and β are unknown, we cannot predict the cross section or differential cross section precisely, instead, we will employ some specific values for the parameters and clarify the physics picture. Moreover, there are constraints on the β -value from the LEP experiments and the $b \rightarrow s\gamma$ transition, namely very small β -value ($\tan\beta < 0.2$) and very light h^0 ($M_{h^0} < 60$ GeV) regions are ruled out.

In fact, as the second Higgs boson h^0 is involved, the total cross section and differential cross section would be different from that predicted by the MSM. However our results show that the change of the total cross section is too tiny for detecting. The physically interesting observation is the differential cross section. We focus our attention on the the possibilities, which depend on the parameters of the model, i.e. due to possible but different parameters of the model, at LEP II energy two peaks protruding out from the background occur in the differential cross section or only a single one does. We will show that even only one peak exists in the s_2 spectrum for LEP II experiments, the MSM and ESM still may predict a different width and height of the peak, hence their combined effect, the event rate, so different from each other that the experiments may distinguish them, if the parameters in ESM are suitable.

(i) In Fig.2, we draw the differential cross section versus $s_2 \equiv (p_b + p_{\bar{b}})^2$ with $\alpha = \pi/4$, $M_{H^0}=100$ GeV, $M_{h^0}=70$ GeV and $\beta = 0.25$ in Model II, then it is found that as s_2 varies, two resonance peaks appear very clearly above the background.

The upper curve which corresponds to the total contribution from all the ten diagrams covers the lower one which only accounts for the two diagrams concerning

H^0 and h^0 . It is noticed that the heights of the peaks heavily depend on the parameter choices (α and β), but the peak signal is obviously above the background and may be observable if the resolution of the measurements on the momenta of \bar{b} and b is fine enough. The widths also depend on the parameters, as shown in eq.(7). The heights of the peaks are almost only determined by the Higgs contribution. At the upper curve one can observe another broad peak at M_Z , it is easy to understand that it comes from the Z -pole at (6) of Fig.1.

For Model I, the situation is very similar, we can clearly observe two peaks at the $d\sigma/ds_2$ spectrum as for Model II, so for saving space, we just omit it.

(ii) It would be interesting to investigate the possibility that if there is only one peak in s_2 spectrum over the possible energy range of LEP II, whether it corresponds to and so confirms the contribution of the Higgs of the MSM or can be something else. Besides the MSM, we may expect another possible solution. Namely, one of the peaks (h^0 or H^0) is located outside our energy scan range, i.e. $M_{h^0 \text{ or } H^0} > \sqrt{s} - M_Z$, so is missing in the figures of differential cross sections. Generally, $M_{h^0}^{2HDM} < M_{H^0}^{2HDM}$, so we suppose that the H^0 of the 2HDM is outside the scan range. Considering that the experimental resolution for measuring the momenta of \bar{b} and b pair is limited and the width of the Higgs resonance is quite narrow, the quantities of ΔN , where $\Delta N = \frac{d\sigma}{\sqrt{s_2}}\Gamma$, relate to the event numbers directly and are not very sensitive to the experimental resolution, let us define the ratio:

$$R = \frac{(\Delta N^{2HDM})|_{h^0}}{(\Delta N^{MSM})|_{H^0}}, \quad (10)$$

and use the ratio R to characterize the difference between 2HDM and MSM. The superscript 2HDM and MSM correspond to the Two-Higgs-Doublet-Model and the Minimal-Standard-Model respectively. R corresponds to the ratio of the events from h^0 predicted by the 2HDM to that from H^0 by MSM, and assuming $M_{H^0}^{MSM} = M_{h^0}^{2HDM}$ but $M_{h^0}^{2HDM} \ll M_{H^0}^{2HDM}$ as well.

The dependence of R on β and α is shown in Figs. 3 and 4 corresponding to Model I and Model II respectively. The meaning of the results will be discussed in

next section.

V Discussions and conclusion

Higgs hunting may be the task for the rest of this century, but we are convinced by the past efforts in both experiments and theories that it is a very difficult job. Any progress along the direction must be very exciting and shed light on the mysterious sector of the Standard Model.

LEP II will run at $190 \sim 205$ GeV C. M. S energy and due to its much clearer background than hadron collider, it is a foreseeable ideal place for Higgs hunting in the recent a few years.

In MSM, after SSB of $SU(2) \times U(1)$, only neutral Higgs remains. The Higgs boson event rate for the bremsstrahlung process $e^+e^- \rightarrow Z^0 H^0$ is known better than 1% including radiative corrections [11]. To measure $e^+e^- \rightarrow Z^0 b\bar{b}$ in fact is measuring a combination of two processes $e^+e^- \rightarrow Z^0 H^0$ and $H^0 \rightarrow b\bar{b}$, especially for the differential cross section at the Higgs peak. Namely if H^0 is not too heavy, the intermediate H^0 can be real. As the authors of ref.[4] showed that in the case the ratio of signal over background in $e^+e^- \rightarrow b\bar{b}Z^0$ is greatly increased and close to unity.

However, if the Higgs sector is not so simple, for example, it includes two or several doublets, the complexity increases. As we discussed above, analysis of the total cross section depends on the employed theoretical models, so a rash conclusion may be misleading. If there indeed exists the second doublet in the Higgs sector, once we observe the total cross section only, which is larger than that the supposed background can give rise to, we still cannot be used it to relate to the Higgs mass as done for MSM. This makes the wish to draw a definite conclusion on Higgs mass from measuring the total cross section of $e^+e^- \rightarrow b\bar{b}Z^0$ pessimistic.

As shown in Fig.2, the differential cross section with $\frac{d\sigma}{d(p_b+p_{\bar{b}})^2} \equiv \frac{d\sigma}{ds_2}$ indeed

demonstrates two peaks which correspond to H^0 and h^0 respectively because H^0 and h^0 both are not too heavy. It certainly is an evidence of ESM. Of course, there is another possibility that M_{H^0} is too large that its peak cannot be allowed to appear by the phase space for the LEP II energy. In this possible case, one probably observe one peak only, but a careful analysis of the measurements, which include the total cross section and differential one, may still help to distinguish it from h^0 of 2HDM or the Higgs boson of the MSM.

In general, it is more interesting to study the case when only one peak exists in the figures for the differential cross section at a precise energy e.g. at LEP II, because in the case the feature of the signal is similar for MSM and 2HDM, whereas it is still possible to indicate whether the peak corresponds to MSM or 2HDM in certain conditions. In the paper, we would like to see the conditions: the experimental measurements are precise enough and the parameters of 2HDM are suitable. In Figs.3,4 we demonstrate the dependence of R defined in last section on the two angles β and α of 2HDM. Thus from the Figs.2-4 we may achieve some understanding of the peak when having the peak well measured. If $R \sim 1.0$, one would not be able to distinguish MSM and 2HDM, while if one may be certain to exclude the uncertainties and to have $R \leq 1.0$ (from Figs.3,4 one may see that there are very rare chances for the model parameters to have $R > 1.0$), one would be able to say the peak is in favor of 2HDM with a possible choice of the model parameters.

In fact, in terms of eq.(10), one can immediately obtain approximate expressions of R for Model I and II. Concretely,

$$R \approx \sin^2(\beta - \alpha) \quad (\text{for Model I}) \quad (11)$$

$$R \approx \sin^2(\beta - \alpha) \frac{1}{0.8 \cot^2 \alpha \cot^2 \beta + 0.92} \quad (\text{for Model II}). \quad (12)$$

The results show that if one resonance of H^0 or h^0 (usually assuming $M_{h^0} < M_{H^0}$) is outside our energy scan range ($M_{H^0} > \sqrt{s} - M_Z$ in our case), for Model I of 2HDM, with a reasonable β range as $\tan \beta > 0.21$, which is constrained by the data of $b \rightarrow s\gamma$ [7][8], we always have $R < 1$, namely the area encompassed by the peak

resulted by the neutral Higgs of the 2HDM is always smaller than that resulted by the MSM Higgs. Whereas, for Model II, there is possibility that $R > 1$, but within a plausible region $0.21 < \beta < \pi/2$ and α not being large, the ratio R is also smaller than unity.

LEP II will provide an integrated luminosity of about 170 pb^{-1} per year [12] with the data taking efficiency less than 25 %. According to the estimation of ref.[4], the MSM can produce less than 100 events every year as LEP II operates at 195 GeV. With the number as a reference, our results indicate that the total cross section and differential cross section can be observed when R is not too small e.g. $R \geq 0.1$, but still vary with the Higgs mass in models.

To determine if the peak corresponds to MSM or 2HDM, one should require $R \leq 0.7$, otherwise a clear judgement is very hard if not impossible at LEP II due to very rare events. From our numerical results shown in Fig.3 and Fig.4, only α and β remain within certain ranges, R can be expected to be less than 0.7 but greater than 0.1. As discussed, the complexity due to the two Higgs doublets cannot be eliminated by the unique process $e^+e^- \rightarrow b\bar{b}Z^0$ at LEP II. In fact, it is very limited for LEP II to solve the problem. As the physical world sets an even messier picture to us, along the direction any progress will be inspiring and encouraging and the measurements on $e^+e^- \rightarrow b\bar{b}Z^0$ are definitely significant in the Higgs hunting process [13][14][15].

Our conclusion is that even though the $e^+e^- \rightarrow b\bar{b}Z^0$ measurements at LEP II can provide us some direct evidence and information about H^0 to indicate MSM or 2HDM if we are so lucky enough that the Higgs mass eventually falls into the experimental ability, the new scenario will begin immediately in fact. To determine the Higgs doublet structure is a complicated and very hard problem with such a few events. A careful measurement on the differential cross section $\frac{d\sigma}{d(p_b+p_{\bar{b}})^2}$ is always useful and helpful, especially for determining the mass of the Higgs.

Acknowledgements

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Figure Captions

Fig.1. The Feynman diagrams for $e^+e^- \rightarrow b\bar{b}Z^0$, where (3) and (4) are that concern H^0 and h^0 respectively.

Fig.2. The dependence of the differential cross section on s_2 for Model II with $\alpha = \pi/4$, $\tan \beta = 0.25$, $M_{H^0} = 100$ GeV and $M_{h^0} = 70$ GeV.

Fig.3 The dependence of R on α and β for model I.

Fig.4 The dependence of R on α and β for model II.